Technical Note 1967-58

P. E. Green
R. J. Greenfield

Application of Large Aperture Array Techniques to Tsunami Warning

29 December 1967

Prepared for the Advanced Research Projects Agency
under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This research is a part of Project Vela Uniform, which is sponsored by the U.S. Advanced Research Projects Agency of the Department of Defense; it is supported by ARPA under Air Force Contract AF 19(628)-5167 (ARPA Order 512).

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

APPLICATION OF LARGE APERTURE ARRAY TECHNIQUES TO TSUNAMI WARNING

P. E. GREEN

R. J. GREENFIELD

Group 64

TECHNICAL NOTE 1967-58

29 DECEMBER 1967

LEXINGTON MASSACHUSETTS

ABSTRACT

A brief examination is made of the potentialities of a single large array like the Montana LASA in providing rapid tsunami warning information from earthquakes at teleseismic distances from the array. It appears that speed and location accuracy of such a station are adequate. Depth determination from depth phase observation is somewhat enhanced compared to that available from a small station, but the reliability of depth determination by the combined use of depth phases, body-surface magnitude differences, and surface wave dominant period is still not as reliable as required. In an Appendix the empirically observed limit on tsunami magnitude imposed by water depth is explained.

This paper is adapted from one of the same title presented at the September 27, 1967 Tsunami Session of the International Association of Physical Oceanography at Berne.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

I. INTRODUCTION

The purpose of this note is to discuss techniques of rapid generation of tsunami warning information by teleseismic measurements in the light of experience gained in two years of experimenting with the Large Aperture Seismic Array (LASA). This array was built in Montana as part of the U. S. Vela Uniform program. The array, which has been described in detail elsewhere,[1] has an aperture of 200 km and uses considerable real time and non-real time digital computation capability to generate some of the interesting seismic source parameters quite rapidly.

Although the installation was intended for monitoring and identifying underground nuclear explosions, it seemed interesting to us to examine the implications of this development for seismic tsunami warning.

In our examination, no attempt was made to consider the use of non-seismic sensors such as tide gauges. In this connection it is useful to point out that teleseismic techniques allow rapid monitoring of tsunamigenic areas that may be remote from tide gauge and localized seismic instrumentation, and that there are many such source areas.

II. REVIEW OF EARTHQUAKE PARAMETERS OF INTEREST

There is no longer any doubt that most tsunamis are caused by tectonic earthquakes occurring under ocean areas. The exact effect that a given tsunami will have on a particular area depends not only on the energy spectrum of the disturbance in mid-ocean during propagation from the source region to coastal areas, but also on the particular resonant frequencies and dissipation factors of the various segments of the coastline contour. A tsunami magnitude m_t has been defined* analogous to seismic magnitude, and based on the amplitude of the largest cycle of the arriving water wave.[2] Hopefully this magnitude parameter should express the intrinsic energy in the seismically generated water wave train near the source. A warning system which would produce a determination of the most probable tsunami magnitude, $\hat{m}_t$, and do so on seismic data alone, would be most useful, and we shall set this, plus determination of epicenter location and origin time, as the objectives in our discussion of tsunami warning provided by large aperture arrays.

There are interesting similarities between the procedures used in providing identification for nuclear test monitoring and those involved in the measurement of source parameters for tsunami warning. For example, the measurement of depth is important in both cases and measurement of the radiation pattern is desirable, but not usually possible. More fundamentally, the procedure of deciding whether to declare

---

* m_t is given in terms of water wave height w (meters) as follows:

w:	< 0.5	1	2	4-6	10-20	> 30
m_t:	-1	0	1	2	3	4

a tsunami warning involves the analysis of observed values of a number of seismic and non-seismic variables, backed up by past history and common sense; this is exactly the situation in deciding whether a clandestine nuclear test or an earthquake has occurred. On the other hand, there is at least one important difference between the test monitoring and tsunami warning problems; in the former case it is the smaller events (below m = 5.0) that are the largest problem, whereas it is not thought that tsunamis generated by earthquakes of magnitude less than 7.0 are likely to be harmful. Therefore, part of the problem of considering how to use tools developed for nuclear test monitoring for tsunami warning consists simply of reorienting our thinking to problems peculiar to large magnitude events.

We proceed now to list those seismic source parameters that have been shown (principally in studies by Iida[3-5]) to influence tsunami magnitude; we then discuss the problem of measuring these parameters using large arrays.

(i) Location

Determining whether the epicenter lies under land or under the floor of the ocean is obviously the first step in the process. Location of the epicenter can be less accurate for higher magnitudes than for the smaller magnitudes simply because the physical size of the fault region increases as magnitude increases. As Fig. 1 shows,[6] minimum dimensions of the fault region at a given magnitude range from about 10 km for magnitude 6.5 to the order of 1000 km as magnitude increases to 8.5. Measurement of the epicenter location to a finer tolerance than these numbers may not be expected to be significant.

It has been found that water depth d at the source has a particularly important bearing on tsunami magnitude, and therefore the epicenter location determined in the observation must be combined with knowledge of water depth, using available empirical data such as Fig. 2, in order properly to take into account the observation of epicenter location. Appendix 1 presents an analysis of the physical factors underlying the empirically observed dependence of m_t on water depth d shown in Fig. 2.

(ii) Seismic Magnitude

In the measurement of seismic magnitude for large events it is customary to use M_s, the magnitude from surface wave data. Iida's data on the relationship between m_t and M_s is shown in Fig. 3. At the lower magnitudes of nuclear test detection interest one usually employs the body wave magnitude, m_b, using the first few cycles of the P wave. From the tsunami warning point of view, one may wish to avoid the extra 15-30 minutes delay after initial detection of P before the surface waves arrive at teleseismic stations. A quick tentative estimate of M_s is available by adjusting the initially determined m_b by the Gutenberg-Richter[7] empirical relationship, $M_s = 1.6\ m_b - 4.0$.

(iii) Focal Depth

The magnitude m_t of the tsunami generated by an earthquake of given magnitude M_s seems to be strongly dependent on focal depth h of the hypocenter as shown in Fig. 4. Due to the scatter of points, much of which is presumably due to differences in source type as much as in differences of actual focal depth, it is probably

not necessary to have extremely accurate measurements of focal depth (say within a few km). Depth measurements to ± 30% or more should be sufficiently accurate. For example, a rapid determination that a particular magnitude 7.5 earthquake lay at a depth somewhere between 100 and 200 km would be quite satisfactory. There is presumably some relationship between vertical extent of a faulting interface and magnitude, analogous to that given in Fig. 1 for horizontal extent. This relationship is not known at present, but it seems clear that the needed accuracy of depth observation decreases with increasing magnitude in some way.

(iv) Radiation Pattern

Both on theoretical and experimental grounds,[8] it is the vertical component of net ocean floor motion that excites the water wave. No thorough study of the relationship of radiation pattern to m_t has been reported in the literature, so that empirical proof is lacking at present. To determine the radiation pattern teleseismically, multi-station fault plane analyses using body waves (initial P-polarity possibly supplemented by S-polarization) or surface waves (by equalizing out the transmission path to each receiver) would be required.

The suggestion has been made that the amplitudes of atmospheric pressure waves generated by an earthquake should be indicative of the amount of vertical displacement produced, and thus of the likely tsunami energy.[9] Unfortunately for warning purposes the sound velocity is only about three times the water wave velocity, as compared to around 20 times for surface waves and 60 times for P waves.

III. SEISMIC SOURCE PARAMETER MEASUREMENTS CURRENTLY BEING REPORTED BY THE LASA STATION

Some of the parameters mentioned above can be measured, and in fact are being measured, in the on-site operation of the single Large Aperture Seismic Array in Montana.[10] Other parameters would require special procedures, and of course, some, notably the nature of the radiation pattern, can never be measured adequately from a single seismic station of any kind.

In the present mode of operation in Montana, automatic event detector circuitry, consisting of narrow bandpass filters followed by threshold alarm devices, trigger whenever the P-phase of an event of larger than the noise level arrives at different portions of the array. One such event detector is attached to each of the 21 subarrays that are distributed over the 200 km aperture and the trigger times are used to compute epicenter locations from the azimuth and horizontal velocity of a hypothetical plane wave giving a least-squares fit to the observed times. The amplitude and period of the strongest half-cycle in the first three seconds are observed for each of the subarrays, and a body-wave magnitude is derived by averaging the magnitudes computed for those subarrays whose outputs meet a certain standard of signal-to-noise ratio (Fig. 5).

In addition to epicenter location and magnitude, current on-site machine operations include measurement of P-coda complexity, as well as several quantities determined in the process of computing the epicenter, namely P-wave azimuth, distance, and horizontal phase velocity. The search for later phases such as pP is

currently done by eye rather than by machine. Figure 6 shows an excerpt from the station bulletin generated at the Montana LASA. Although this is currently generated only within a day of the occurrence of the event, the procedure is highly automatic and the program[10] was written so that it can be operated on-line in real time if desired.

Figure 7 summarizes results on accuracy of epicenter location in regions of the earth where time station corrections of the various LASA subarrays are known from previous well-located events. (Most tsunamigenic earthquakes may be expected to originate from such well-studied regions.) Comparison with Fig. 1 shows that the aperture of the array is sufficient to meet the requirement that above magnitude 7.0 it determines a point within a tolerance not significantly wider than the fault size appropriate to that magnitude.

The body-wave magnitudes reported in the LASA station bulletin (averages over many subarrays) have been compared with those reported by individual subarrays and with the averages over many globally separated stations reported by the U.S. Coast and Geodetic Survey. It was found that the LASA body-wave magnitudes are considerably more reliable than single-station magnitudes and approach the CGS worldwide averages in reliability. This is considered to be due to averaging over a scatter of received amplitudes which exists among the various subarrays of the array.

As noted earlier, one observation that is being reported in the bulletin but has not been automated is the identification of depth phases (pP, sP). This must now be done by manual observation of a side-by-side display of the traces from the many

subarrays. As Fig. 8 shows, this procedure is highly effective compared to observations from individual small array stations, but even so, results in the determination of depth for at most 40% of the earthquakes that were observed.

Surface wave magnitude can be measured trivially at a station such as the Montana LASA, although it is not currently being observed on-line. The standard definition for surface-wave magnitude, M_s, involves measurements at 20-sec period. A computer program to measure amplitude at 20-sec period, and output the value of M_s using computed epicentral distance and a stored table of the distance factor, is a minor modification of existing short-period programs mentioned earlier. The dominant period of the surface wave can also be easily measured.

IV. FURTHER METHODS OF DEPTH ESTIMATION

In comparing the list of desired source parameter measurements given in Section II with the present measurement practice at the Montana LASA, it becomes clear that better depth measurement probably is the most important thing whose improvement might be attempted using the LASA station. In regions of the world where dense networks of local stations are available, depth measurement from P and S travel times[11] is a routine part of the tsunami warning cycle. However, as the Chilean event of 1960 demonstrated, dangerous tsunamis often originate in areas that are seismically active but poorly instrumented from the real time standpoint. Also, large events sometimes occur in areas that are only moderately active on a long-time basis. All in all, any improvement in teleseismic depth measurement would be a worthwhile contribution.

We were led by these considerations to inquire into methods other than identification of depth phases (pP, sP) for depth estimation on large events using the large array. We considered three methods and report the results here, which although not very encouraging, might prove to be of some interest.

The first involves comparison of "apparent" body and surface wave magnitudes, that is, magnitudes computed from amplitude, period, and distance using the standard formulae with no correction for depth. For an earthquake of given energy, the apparent body wave magnitude should increase and the surface wave magnitude decrease as focal depth increases. Figure 9 shows data on such M_s vs m_b readings for a number of

Pacific and circum-Pacific earthquakes. The depths are those reported by the U. S. Coast and Geodetic Survey.* The Gutenberg-Richter relationship is shown as a solid line.

The scatter of the data is quite large and the dependence on the depth quite weak, although a slight systematic decrease in M_s with depth for fixed m_b is perceptible. For example, the data suggest that using an arbitrary decision rule that any event lying above the dashed line is shallower than 100 km and anything below is deeper, 67% of those having $h < 100$ and 67% of those with $h > 100$ km would have been correctly labeled. Other data on depth dependence of $M_s - m_b$ are given by Bath[12] who used single horizontal instruments on events with clear pP. In both his experiments and ours, the scatter is very large and it is thus clear that at best M_s vs m_b measurements provide only collateral information on depth and cannot be used as the sole criterion.

The second approach is based on the assumption that there is a general shift of the spectral concentration of surface wave energy toward longer periods for increasing depth.[13] Figure 10 shows data in the form of P_M the period of maximum LASA surface wave amplitude, vs focal depth reported by the U. S. Coast and Geodetic Survey. A general increase of P_M with depth is seen, even though the scatter is quite severe.

---

* To check that the cause of poor performance of this criterion might be poor depth measurement, those events of Fig. 9 with visible depth phases (34 of the total 129) were examined separately, with much the same result.

The third approach which has so far proved to be completely unsuccessful, involves examination of the ratio of higher order surface wave amplitude relative to the fundamental, a factor dependent on both depth and propagation path.[14] It has been noted, for example, that many deep focus earthquakes show such higher order excitation while the fundamental is virtually absent. We examined 40 Pacific and circum-Pacific teleseisms in the m_b = 5.2 to 6.2 range without observing any higher order surface wave energy on single traces. The experiment should be extended to higher magnitude data as they become available.

V. FLOW DIAGRAM FOR DETERMINATION OF TSUNAMI MAGNITUDE

A stepwise procedure for determination at a single large array of those factors influencing the measurement of the most probable tsunami magnitude $\hat{m}_t$ is implied in the discussion given in the preceding pages. Figure 11 shows a conceptual flow diagram of how such a procedure might operate. Above the dashed line are those determinations that can be completed in little more than the time taken for the P-wave to propagate across the array. The operations below the dashed line require the arrival of the surface waves some tens of minutes later. Computer programs and considerable experience exists for those operations in the shaded area of the figure (except that depth phase observation has not been automated).

VI. CONCLUSION

Techniques currently in daily use with the Large Aperture Seismic Array allow location, origin time, and magnitude measurements to be made autonomously within this one station with the accuracy required of a seismic warning network. Depth measurement is still unreliable, although the array does provide visibility of depth phases superior to that available from smaller stations. Some initial work on several other methods of depth determination was mentioned. We are continuing to study such criteria individually, as well as the joint application of such parameter measurements, each of which is only partially effective by itself.

REFERENCES

1. Four papers on the Large Aperture Seismic Array, Proc. I.E.E.E., 53, 1821-1859, December 1965.

2. A. Imamura, List of Tsunamis in Japan, Zisin, Ser. 2, 2, 23-28, 1949.

3. K. Iida, Magnitude and energy of earthquakes accompanied by tsunami, and tsunami energy, J. Earth. Sci., Nagoya Univ., 6, 101-112, December 1958.

4. _____, Magnitude, energy, and generation mechanisms of tsunamis and a catalog of earthquakes associated with tsunamis, IUGG Monograph No. 24, (Pacific Science Congress--Tsunami Meeting, Honolulu, 1961), 7-18.

5. _____, A relation of earthquake energy to tsunami energy and the estimation of the vertical displacement in a tsunami source, J. Earth Sci., Nagoya Univ., 11, 49-67, June 1963.

6. F. Press, Dimensions of the source region for small shallow earthquakes, Proc. VESIAC Conference on Shallow Seismic Events in the 3 to 5 Magnitude Range, VESIAC, Inst. of Sci. and Technology, U. of Michigan, February 1967.

7. B. Gutenberg and C. F. Richter, Magnitude and energy of earthquakes, Ann. Geophys., 9, 1956.

8. W. G. Van Dorn, Source mechanism of the tsunami of March 28, 1964 in Alaska, preprint, 1967.

9. G. Pararas-Carayannis and M. J. Vitousek, On the utilization of atmospheric data for the evaluation of potential tsunamis, U. of Hawaii, Institute of Geophysics, Rec. No. 8, October 1966.

10. P. L. Fleck, FASTABUL (A Fast Automatic Station Bulletin Program), M.I.T., Lincoln Laboratory Technical Note 1967-3, 6 January 1967.

11. K. Wadati, T. Hirono, and S. Hisamoto, On the tsunami warning service in Japan, IUGG Monograph No. 24, (Pacific Science Congress--Tsunami Meeting, Honolulu, 1961) 138-146.

12. M. Bath, The problem of earthquake magnitude determination, Publ. of Bur. Cent. Seism. Internat., Strasbourg, Ser. A, 19, 5-63 (Presented at IUGG Assembly, Rome, 1954) see esp. p. 41.

13. P. D. Marshall, U.K.A.W.R.E., private communication, 1967.

14. S. Crampin, Higher modes of seismic surface waves: Preliminary observations, Geophys. J., 9, 37-57, 1964.

15. W. G. Van Dorn, Tsunamis, "Advances in Hydroscience," 2 (Academic Press, New York; 1965).

APPENDIX 1

LIMITATION OF TSUNAMI MAGNITUDE FOR SHALLOW WATER SOURCES

Figure 2 shows that for a given depth of water, d, in the source region, tsunamis will be generated only up to a limiting tsunami magnitude, m_t. This limit is in contradiction to simple energy considerations which state that the potential energy available in the displacement of the water from equilibrium is dependent upon the vertical movement of the sea floor and upon the area of disturbance but not upon the water depth. In this note we will attempt to explain Iida's observed limit.

The proposed explanation is that in shallow water, where the phase velocity $\sqrt{gd}$ (g is the gravitational acceleration) is small, the water wavelengths for periods typical of tsunamis are much shorter than the fault lengths, L, of large earthquakes. Therefore, large earthquakes are not able to excite efficiently tsunamis in shallow water. We show that this explanation can be used to find a limit on m_t, as a function of d, which is in quantitative agreement with that found by Iida and shown in Fig. 2.

For a given sea floor displacement which is characterized by a diameter L, there is a water wave period, T_m, which receives maximum excitation. Van Dorn[15] gives

$$T_m = \pi L/\sqrt{gd} \qquad (1)$$

(all lengths in meters). Expression (1) is relevant to a particular axially symmetric sea floor displacement, but is correct to perhaps a factor of 2 for any reasonable deformation. If T_m is greater than the normally observed tsunami period T'_m, then the tsunami will not be efficiently excited. Therefore, large tsunamis will be excited only if

$$L < \frac{\sqrt{gd}}{\pi} T'_m \quad \text{meters} \tag{2}$$

Let us associate L with fault length. Then L increases with earthquake magnitude, M_s as shown in Fig. 1. From this curve we have adopted the relation

$$L = 10^{[(M_s/1.25) - 1]} \quad \text{meters} \tag{3}$$

We find from (1) and (3) that the upper limit of M_s for which a tsunami will be excited, for a given h, is

$$M_s < 1.25 \left[1 + \log \frac{\sqrt{gd}}{\pi} T'_m \right] \tag{4}$$

Iida[5] found an empirical relation for shallow focus earthquakes between m_t and M_s.

$$M_s = .385\, m + 7.08 \tag{5}$$

We expect relation (5) to hold only until h becomes too large for given meter length.

Using this to eliminate M_s in (4) gives a limitation on m_t as

$$m_t < \frac{1}{.385} \left[-9.83 + 1.25 \log \frac{\sqrt{gd}}{\pi} T'_m\right] \tag{6}$$

Periods of the major tsunami waves rarely exceed 30 to 40 minutes (see Reference 4). If we adopt a value $T'_m = 30$ min, (6) becomes

$$m_t < -3.50 + 4.81 \log \sqrt{d} \tag{7}$$

Formula (7) is plotted as the dotted line on Fig. 2. Noting that a change of a magnitude unit in m is only a factor of 2 in amplitude, we see that (7) gives a good agreement to the observational limit found by Iida.

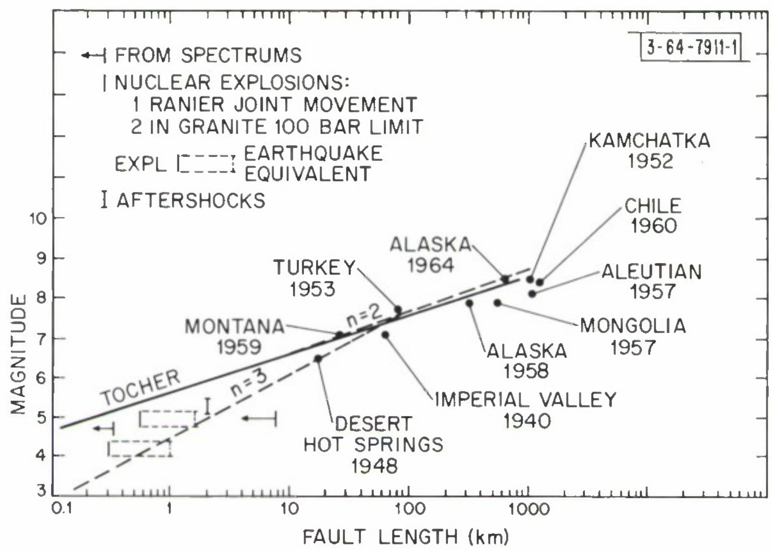

Fig. 1. Fault length-magnitude relations (from Press[6]).

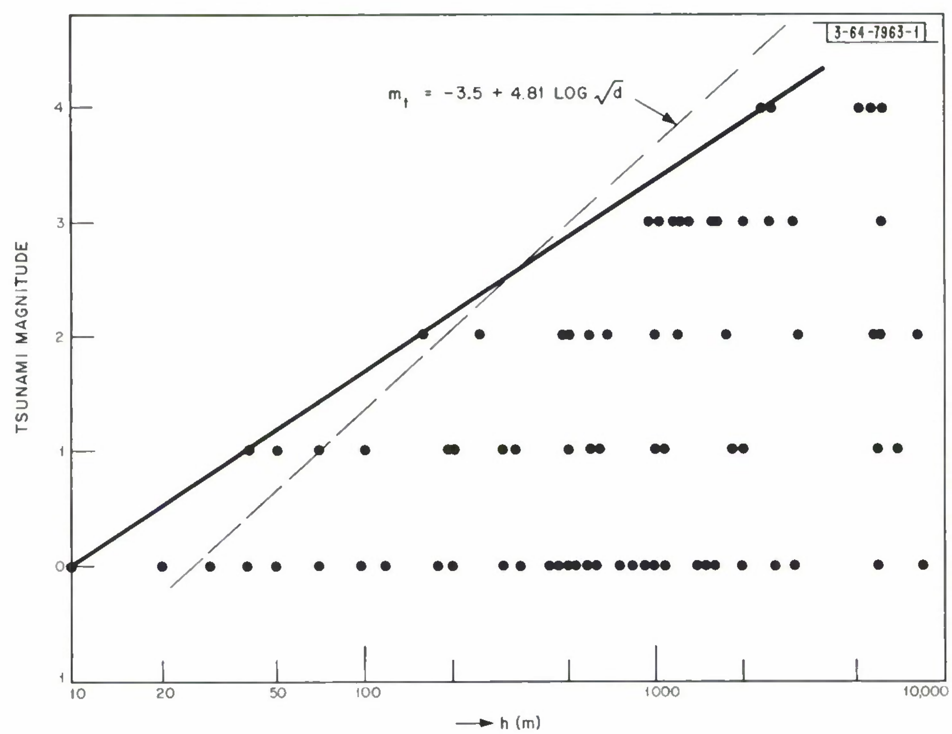

Fig. 2. Relation between tsunami magnitude m_t and water depth d at the earthquake epicenter (after Iida[4]). See Appendix.

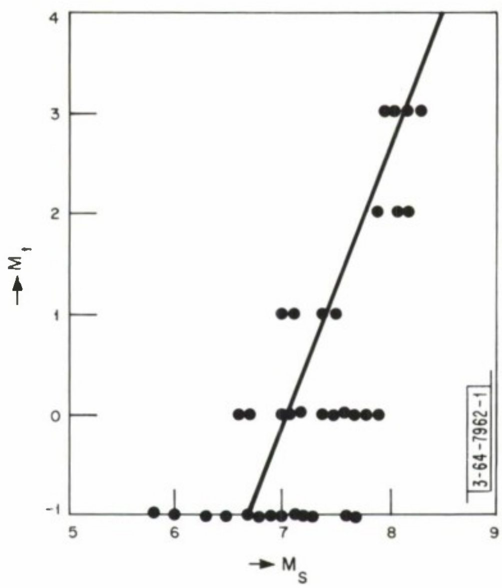

Fig. 3. Relation between earthquake magnitude M_S and tsunami magnitude m_t (Iida).

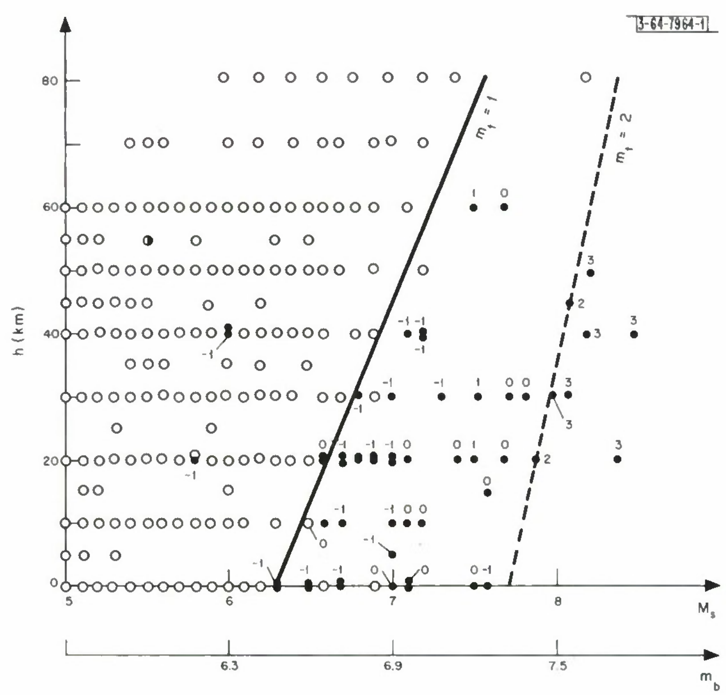

Fig. 4. Relationship between M_S, m_t, and focal depth h. (Iida) o = earthquake not accompanied by tsunami, o = earthquake accompanied by tsunami.

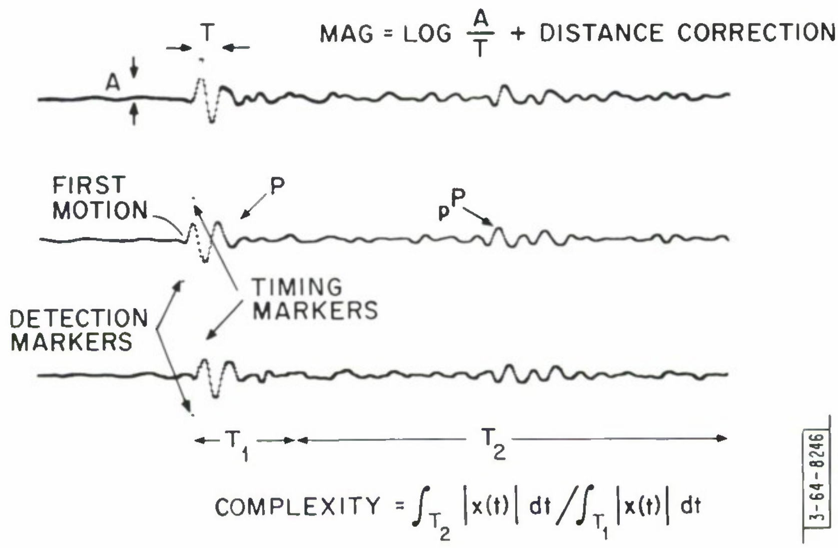

Fig. 5. Output traces for three subarrays, illustrating measurement of seismic signal parameters.

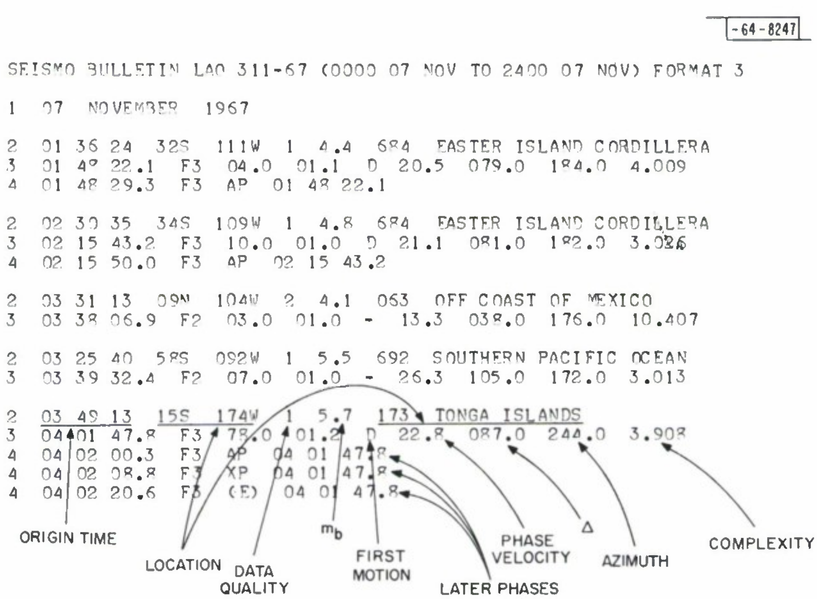

Fig. 6. Excerpt from current LASA station bullet (AP = pP, XP = sP, (E) = emergent phase).

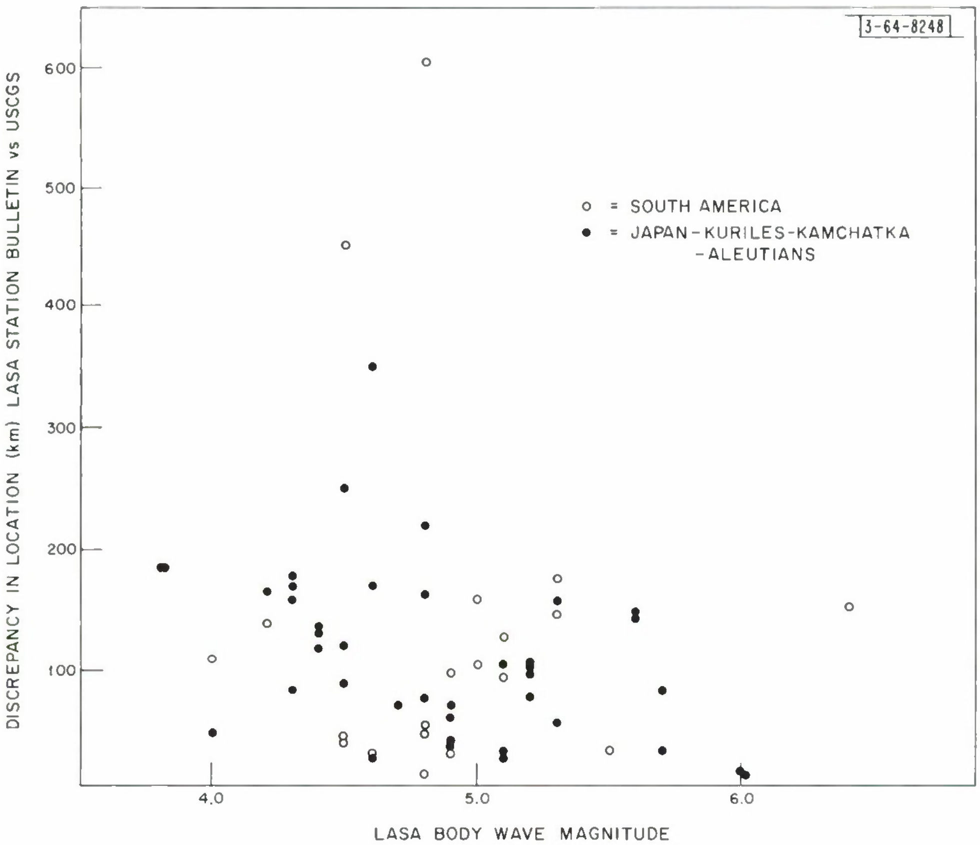

Fig. 7. Error in location vs P magnitude. Month of October 1967.

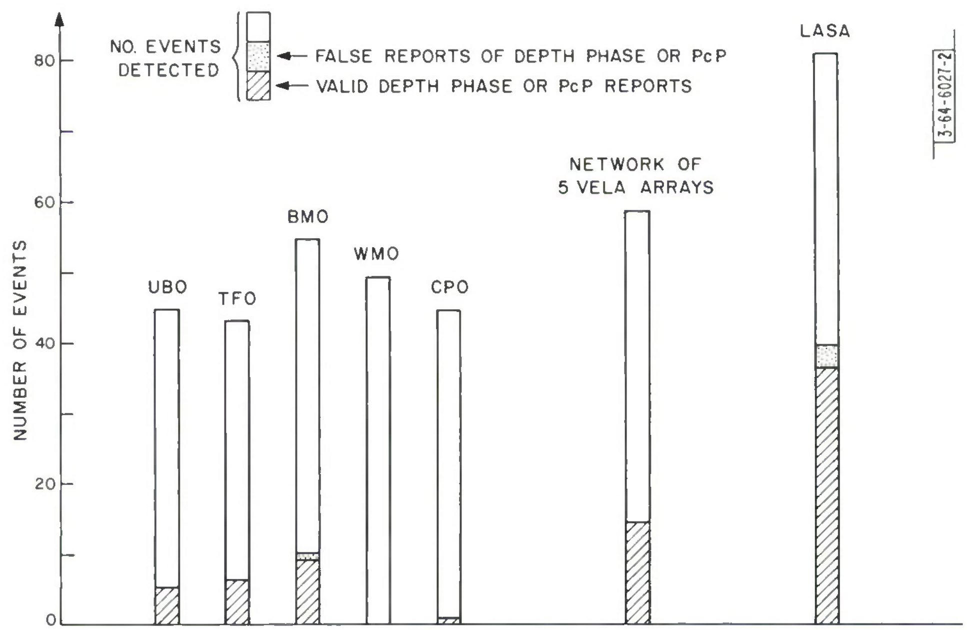

Fig. 8. Relative efficacy of depth phase observation by the LASA and five Vela Observatory arrays. Data obtained by comparing station reports of phases within 60 sec after P with computed depths reported by U. S. Coast and Geodetic Survey.

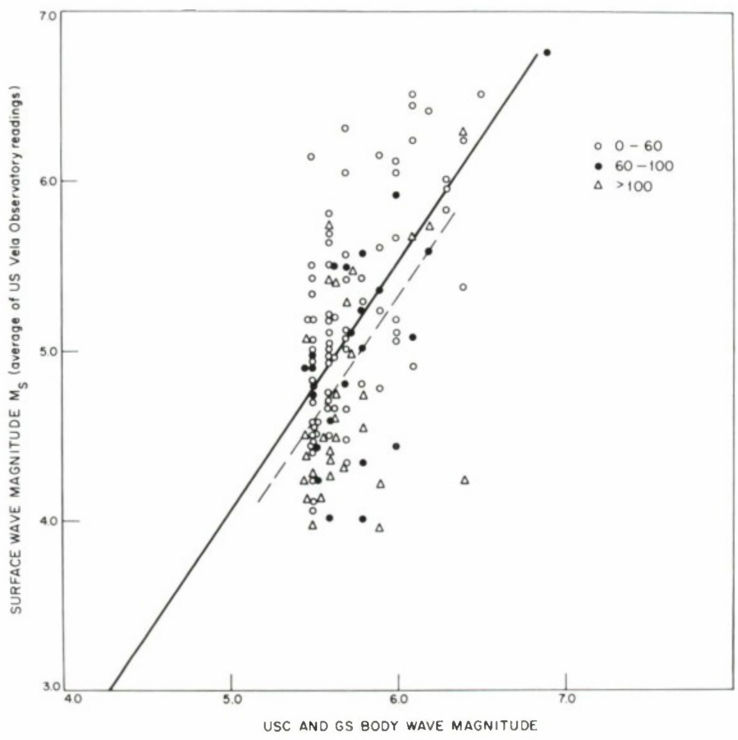

Fig. 9. Surface wave magnitude M_s vs body wave magnitude m_b for Pacific and circum-Pacific events in three depth ranges. (Vela array readings; an event-by-event comparison with LASA observations on 20 earthquakes showed no significant differences.)

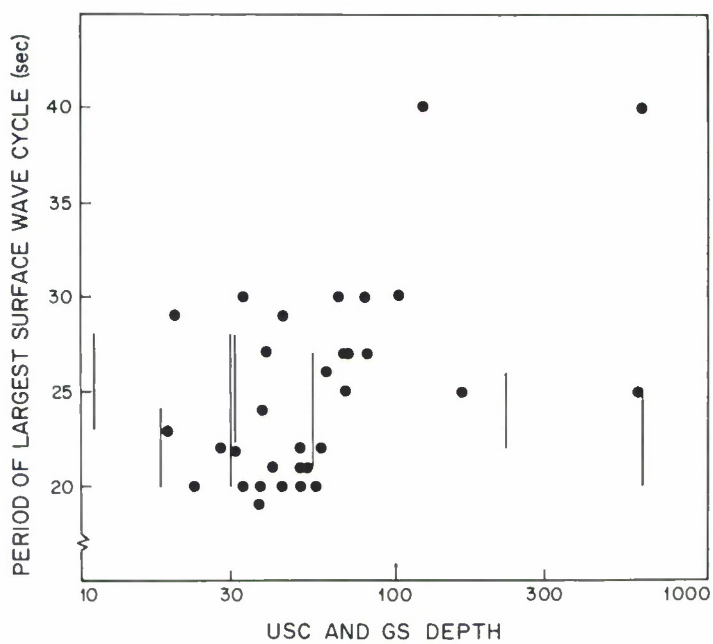

Fig. 10. Dependence of dominant surface wave period P_M on depth.

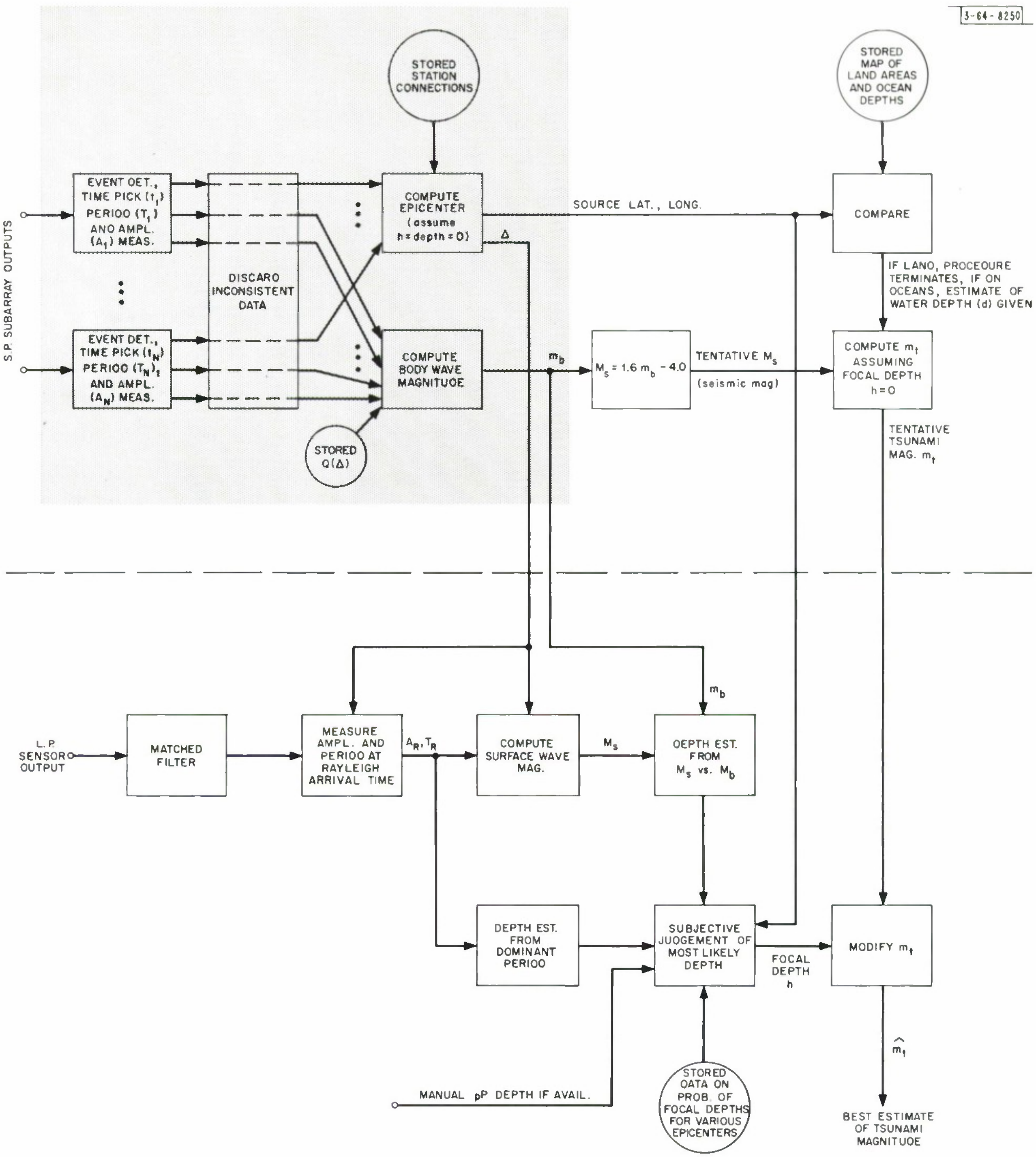

Fig. 11. Flow diagram of the sequence of large array signal handling operations for generating tsunami warning information. (Shaded area indicates currently employed station bulletin program.)

DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified	2b. GROUP None

3. REPORT TITLE

Application of Large Aperture Array Techniques to Tsunami Warning

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Note

5. AUTHOR(S) *(Last name, first name, initial)*

Green, Paul E.
Greenfield, Roy J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
29 December 1967	32	15

8a. CONTRACT OR GRANT NO. AF 19(628)-5167	9a. ORIGINATOR'S REPORT NUMBER(S) TN-1967-58
b. PROJECT NO. ARPA Order 512	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-67-594
d.	

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

A brief examination is made of the potentialities of a single large array like the Montana LASA in providing rapid tsunami warning information from earthquakes at teleseismic distances from the array. It appears that speed and location accuracy of such a station are adequate. Depth determination from depth phase observation is somewhat enhanced compared to that available from a small station, but the reliability of depth determination by the combined use of depth phases, body-surface magnitude differences, and surface wave dominant period is still not as reliable as required. The empirically observed limit on tsunami magnitude imposed by water depth is explained.

14. KEY WORDS

aperture array techniques	Montana LASA	teleseismic measurements
tsunami warning	earthquakes	